PAPER III

The complexity and challenges of determining GHG (greenhouse gas) emissions from grid electricity consumption and conservation in LCA (life cycle assessment)

A methodological review

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Review

The complexity and challenges of determining GHG (greenhouse gas) emissions from grid electricity consumption and conservation in LCA (life cycle assessment) – A methodological review

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ABSTRACT

The way in which GHG (greenhouse gas) emissions associated with grid electricity consumption is handled in different LCA (life cycle assessment) studies, varies significantly. Apart from differences in actual research questions, methodological choices and data set selection have a significant impact on the outcomes. These inconsistencies result in difficulties to compare the findings of various LCA studies. This review paper explores the issue from a methodological point of view. The perspectives of ALCA (attributional life cycle assessment) and CLCA (consequential life cycle assessment) are reflected. Finally, the paper summarizes the key issues and provides suggestions on the way forward. The major challenge related to both of the LCA categories is to determine the GHG emissions of the power production technologies under consideration. Furthermore, the specific challenge in ALCA is to determine the appropriate electricity production mix, and in CLCA, to identify the marginal technologies affected and related consequences. Significant uncertainties are involved, particularly in future-related LCAs, and these should not be ignored. Harmonization of the methods and data sets for various purposes is suggested, acknowledging that selections might be subjective.

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1. Introduction

The production and distribution of electricity consumed makes a significant contribution to the overall GHG balances of various products and processes. Electricity differs significantly from many other energy carriers, as it cannot be stored as such, and is therefore consumed virtually at the same time as it is produced. Electricity can be transmitted for long distances via overhead lines and power cables. Within an electrical network, the consumption and thus also the production typically varies between times of day, seasons, and between years. Furthermore, the electricity production mix varies from one moment to another, and can be very different in different electrical grids. Transmission of electricity between utilities in neighboring regions has been common for many years. Transmission is economically efficient, as it reduces the overall requirement for reserve margins and balances the fluctuations in load within the market area [41]. These specific properties make the assessment of GHG emissions associated with the individual process of consuming or conserving grid electricity a complex and challenging procedure. However, the particular information is highly relevant and required for almost any environmental impact assessment in one form or another.

GHG emissions associated with electricity consumption have been considered in an extensive number of studies related to the cost externalities of electricity consumption [e.g 1–6]., energy system analysis [e.g 6–10]., life cycle assessment (LCA) [e.g 9,11–13], and in the context of CDM (Clean Development Mechanism) project methodologies [14]. The perspectives on environmental impact assessment vary from product or process level to macro level, such as the overall energy system of a country. The appropriate methodology for analyzing the question at hand should be selected accordingly.

LCA is a methodological framework for estimating and assessing the environmental impacts related to the life cycle of a product or process [15,16]. Typically, a LCA study covers the life cycle of a product or process from 'cradle to grave' but may also be limited to

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a certain part of the life cycle, for instance the use phase. The LCA is initiated by defining the goal and scope; this is followed by a life cycle inventory, a life cycle impact assessment and an interpretation of the results [17,18]. The ISO standards ISO 14040, 14044 [17,18] guide the basic framework of LCA, but do not provide guidelines on how, in particular, GHG emission estimates of electricity consumption should be determined. The estimates used in LCA of various products may vary significantly, with no clear reasoning behind the assumptions used; which may make the results confusing and disparate. A similar problem has been recognized within cost externality studies [19]. Furthermore, in LCA studies the uncertainty analysis is often lacking or considered only cursorily [20]. The uncertainty in LCA is due to methodological choices, parameters, and models [21]. In addition, variation in the results is due to spatial and temporal variability and variability in objects and sources [21]. The comprehensive uncertainty and sensitivity analysis should consider all the above-mentioned aspects.

The development of LCA has led to a definition of two main LCA categories: *attributional* and *consequential* [16,22]. *Attributional* LCA (hereinafter *ALCA*) has been defined as a method "to describe the environmentally relevant physical flows of a past, current, or potential future product system," [23]. It can be used to calculate the GHG emissions of every product produced in the economy at a given point in time. Thus, the GHG emissions from an appropriate electricity production mix can be attributed to each of the consumption points within the time frame considered, resulting in average emissions for each kWh of electricity consumed.

Consequential LCA (hereinafter *CLCA*) can be defined as a method for describing how environmentally relevant physical flows would have been, or will be, changed in response to possible decisions that would have been or will be made [16,23]. The CLCA methodology often includes the markets affected by decisions [24]. Momentary changes in the consumption of electricity influence the marginal production unit. Therefore, marginal data should be used to describe the impact of such changes. In reality, consequences caused by a decision to change electricity consumption may be far reaching in time and space. These issues may also be taken into account in CLCA [24]. The number of consequential LCA studies has increased recently, but only a few studies have systematically aimed to determine marginal data for electricity consumption [8,9,25]. Marginal emission factors for grid electricity are also applied in CDM projects, dealing with replaced electricity production or electricity efficiency improvements, to earn CER (certified emission reduction) credits under the Kyoto Protocol [26,27].

Curran and colleagues [22] review the issues related to electricity data for life cycle inventories. They summarize the complex matter at a general level, but do not discuss in detail the significance of the selection of the approach, and variation and uncertainty related to the data. Ekvall et al. [23] discuss normative ethics and methodology selection for LCA in general using electricity consumption as a case study. Weber et al. [28] treat the consequences of the results of using various standards, protocols, and reporting guidelines when estimating emission factors for grid-based electricity. Mathiensen et al. [25] and Lund et al. [9] consider the uncertainties related to the identification of the marginal electricity production technology within a market area. Only a few studies have been published overall on the methodological issues and data uncertainties, and a comprehensive picture is still lacking.

This methodological review explores the complexity and challenges of determining GHG emissions from individual processes that consume or conserve grid electricity. The critical issues and uncertainties involved are discussed. The main objective of the paper is to structure the significance related to selecting appropriate methodologies and data sets for various research questions at hand. The viewpoints of ALCA and CLCA approaches are reflected. The examples given are mainly from the EU (European Union), but the same conclusions can be applied to any operating electricity market.

2. Challenges in the assessment procedure

2.1. Determination of GHG emissions for electricity production and distribution

In order to discuss the GHG emissions of electricity consumption, aspects related to various forms of electricity production need to be explored. Direct GHG emissions, namely CO_2, CH_4 and N_2O, are generated in electricity production based on the combustion of fuels like coal, coke, crude-oil-based products, natural gas, peat, wood and other biomass fuels. These emissions are highly dependent on the composition and quality of the fuel (including heating value and moisture content), and the technological characteristics of the power plant (including efficiency). CO_2 emissions are typically the dominant GHG emissions from fuel combustion but CH_4 and N_2O may also be relatively significant for certain technologies [29,30]. According to World Energy Council [31], GHG emissions in terms of CO_2-eq. per kWh electricity produced from fuel combustion are typically in the order of 1000–1300 g for brown coal, 800–1000 g for coal, 600–700 g for heavy fuel oil, and 350–400 g for natural gas condensing power.

Besides direct emissions from fuel combustion, electricity production causes indirect GHG emissions released as part of the supply of the fuels, and production of the infrastructure and power plants. These upstream GHG emissions for electricity production based on fossil fuels may be difficult to assess accurately, but are typically estimated to be much lower (from only a few percent to some 20%) compared to direct emissions from fuel combustion [e.g 31,32]. As fossil fuel combustion dominates electricity production in many countries, the upstream emissions typically constitute a relatively low share of the GHG emissions of the overall electricity production mix of countries [33–35]. For biomass-based electricity, however, the biomass provision and related carbon stock changes in the soil and biomass typically produce the most significant proportion of the associated GHG emissions. According to many recent studies, significant uncertainties are involved in these emissions, and they may even make the GHG performance of biofuels inferior to that of fossil fuels [e.g 36–38].

GHG emissions from electricity production that are not based on fuel combustion, such as wind, hydro, solar and nuclear power, are associated completely with the capital goods and the upstream GHG emissions. According to the World Energy Council [31], GHG emissions in terms of CO_2-eq. per kWh electricity produced are estimated at 7–22 g for wind power, 5–90 for hydro power, 13–104 g for solar power and 3–40 for nuclear power.

When electricity power plant produces multi-products such as power, heat, steam, cooling or refinery products, the problem of emission allocation is encountered. Allocation is a widely recognized and challenging methodological problem in LCA, and the selection of an allocation method typically has a significant impact on the results [39]. This is illustrated in Fig. 1 for a hypothetical coal-fired CHP (combined heat and power production plant). Graus and Worrel [40] studied the impact of various allocation methods on national average GHG emission intensity for a number of countries. They showed that the impact of allocation method is the most significant for Belarus, Denmark, Finland, Kazakhstan, Lithuania, and the Russian Federation. These countries utilize CHP the most in their electricity production. In 2008, electricity produced in CHP plants corresponded to some 10% of the gross electricity production in OECD countries [41], yet the share can be significantly higher for certain individual countries [42].

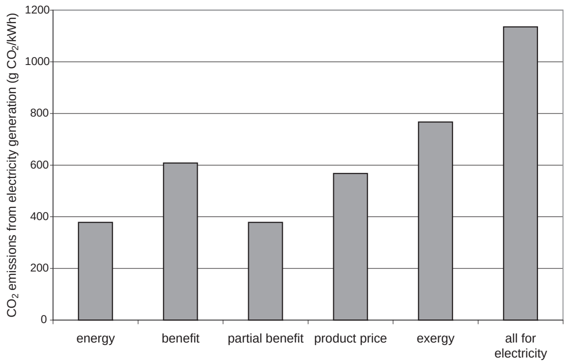

Fig. 1. The influence of various allocation methods on CO_2 emissions from electricity production for a hypothetical coal-fired CHP-plant (power to heat ratio equals 0.5 and the overall efficiency is 90%). The exergy content is assumed to be 1 and 0.24 for electricity and heat, respectively. The economic value of the electricity is assumed to be twice that of heat. In the benefit method, the emissions are allocated to power and heat in relation to the assumed alternative forms of production (condensing power with 39% efficiency and heating boiler with 90% efficiency). In the partial benefit method, emissions are allocated to heat on the basis of the fuel consumption of alternative heat production (90% efficiency), and the remaining share is allocated to power. The absolute numbers are for illustrative purposes only.

GHG emissions resulting from electricity supply - from a power plant to an electricity consumer - also depend on the own electricity use of the power plant and pump storage, heat pumps, and electric boilers, as well as on the transmission, distribution, and transformation losses. Altogether they contributed roughly 14% in OECD countries and 17% world-wide in 2008 [41]. Graus and Worrell [40] found a range of 8–44% within a number of countries. Regarding electricity consumption, these factors should be taken into account. However, it is an open issue how they should be allocated between high, medium, and low voltage consumers, and furthermore, between various transactions. Liberalization of the electricity market allows bilateral contracts between the suppliers and the buyers. In a fully deregulated system, the generators are responsible for their respective loads and their share of transmission losses [43]. This concept leads to confusion in the sharing of transmission loss and the reactive power generated [43]. Gomez et al. [44] concluded that total losses allocated to a transaction may differ significantly depending on the allocation methodology adopted. A common practice involves attributing them to various consumption points based on the average within the region under consideration (e.g. a country). Differentiation between consumers and transactions raises an issue of allocation.

2.2. Determination of the appropriate electricity production mix in ALCA

When estimating the GHG emissions of the electricity consumption of certain process in ALCA, a common practice involves using the average national statistical GHG emissions for electricity production [28]. An example of such a study is Izguierdo et al. [13]. This may be due to the good availability of the annual national statistics, the assumption that the process electricity consumption is constant through time, and the assumption that electricity consumption within a country reflects production within that particular country. Smaller and larger regions than a country are also used [e.g 11]. The BIOGRACE project provides harmonized rules for the calculation of biofuel greenhouse gas emissions in Europe and determines that emissions calculated from grid electricity in Europe should be an average for the EU [45]. The decision to select a smaller or larger region for the determination of the electricity production mix for ALCA is important but arbitrary, as there is no 'correct' choice and there are different types of equity issues involved [28]. Regardless of the choice, the use of annual national or regional statistical average figures in ALCA involves several problems.

The annual national (or regional) average production mix of the electricity may vary significantly from year to year, for instance due to changes in electricity demand, fuel mix, technology portfolio, availability of hydro power, and net imports. For example, in Finland the minimum and maximum annual average CO_2 emissions from electricity production between 1990 and 2002 vary by 20% from the average of the particular period (calculation based on [42]). Consequently, using data for only one statistical year in LCA may significantly reduce the reliability and the applicability of the results to describe the situation for other years.

The variation within a particular year is lost when using annual average figures. The difference in annual and shorter time periods may be highly relevant, in particular when assessing the GHG emissions of a process that operates mainly or only during peak-load hours and when there is significant variation in electricity production mix between peak and base load. For example, Blum et al. [12] studied CO_2 emission savings related to ground source heat pump systems by using an annual average German electricity mix and comparing it with a regional electricity mix for electricity consumption. Similarly, Saner et al. [11] carried out a life cycle assessment of shallow geothermal systems used for heating and cooling by determining the GHG emissions of the electricity consumption by using the annual average electricity mix of Continental Europe and other types of annual average electricity mixes for 2006. Both studies exclude the fact that the electricity consumption of heat pump systems varies significantly between warm and cold seasons. Also, it is very likely that the electricity production mix is different in cold and warm seasons. Thus, examination of the average electricity production mixes studied and the particular consumption curves at a more detailed level, e.g. by months, may probably have influenced the results. When the electricity consumption of a process is not constant throughout a year, it may be reasonable to use figures for shorter time periods instead of annual average figures. However, the availability of the data may generate a practical problem.

Some proportion, minor or major, of the electricity consumed within a country may be produced outside the boarders of the country. Examples of countries where a major proportion of the final electricity consumption is based on imports are Benin, Congo, Lithuania, Luxembourg, Mozambique, the Republic of Moldova, Switzerland, and Togo [46]. Correspondingly, some countries, for example Lithuania, Luxembourg, Mozambique, Paraguay, Slovenia, and Switzerland, export a significant share of their electricity production to other neighboring countries [46]. Therefore, it is justifiable to argue that the average national figures do not reflect the GHG emission profiles of the countries' electricity consumption if they are not adjusted by exports and imports of the electricity. The data is probably available for this kind of adjustment at an annual level [e.g 41]. However, it may prove difficult to find appropriate data which would correspond objectively to the electricity trade by taking into account the precise timing of the trade. The problem caused by the electricity trade between countries can be reduced or avoided by determining a market area larger than a country (e.g. the EU). However, then the electricity consumed within a country does not necessarily reflect the characteristics of the electricity production mix and transmission of that country. As electricity transmission capacity is also limited within a country, it may be reasonable to consider regions smaller than a country in determining the appropriate electricity production mix. Then the problem of considering the electricity transmission between regions is again encountered.

The electricity is typically purchased from the electricity sellers who supply electricity from very different forms of production to different types of customers. Instead of a national or regional average production mix, it may be justifiable to use electricity-seller-specific average figures based on contracts between the seller and the consumer. However, it may be difficult to construct such figures, as the sellers may not be the producers, or they may own only part of certain power plants and the ownership shares may change over time. In the Nordic countries, where one of the world's most sophisticated electricity market exists (Nord Pool), the electricity producers sell a significant amount of the electricity through the exchange to retailers with whom the customers are contracted [47]. This causes a transparency problem between electricity purchased and produced.

In a liberalized electricity market such as that of the EU, consumers can choose their electricity supplier based on prices but also on qualitative criteria such as environmental impacts [48]. 'Green electricity' can be defined as electricity that is produced from renewable sources and that has been differentiated from other electricity products and marketed as being environmentally friendly based on certain criteria [49]. The customers purchasing 'green electricity' might like to consider that the electricity consumed by their processes reflects the mix of the particular 'green electricity' instead of the average mix of the electricity seller or region. This is justified also by the fact that the price of 'green electricity' is typically higher compared to 'regular electricity'. This kind of approach would require the determination of 'contract-based' GHG emission intensities for the electricity. In addition, an allocation problem related to losses is encountered, which has to be resolved.

2.3. Determining the marginal technology and consequences in CLCA

ALCA does not reflect GHG impacts of the change in electricity consumption, but it can be used to describe GHG emissions of the average consumption at a given point in time. When the goal is to study the change caused by a particular decision, CLCA can be used. In general, Ekvall and Weidema [24] determined the identification of a marginal technology as a five step process. The current CDM methodology advises project participants to apply six steps in calculating the marginal emission factor to be applied [27]. According to Lund et al. [9] the current 'state-of-the-art' method in CLCA is to identify the long-term change in power plant capacity and to assume that the marginal supply will be fully produced at such a capacity. Traditionally, coal or natural gas has been assumed to reflect the marginal electricity production technology in CLCA (Frees and Weidema [50]; Weidema [51]; Schmidt et al. [52]). The chapters following explore the critical issues related to the determination of appropriate marginal technology and consequences for CLCA.

2.3.1. Short-term marginal technology

Instant GHG emissions from electricity production in a market area depend on the existing technology and the relative operational costs of different production units. In an operational electricity market, a marginal increase or decrease in electricity consumption changes the production of the power production unit that is on the margin of the variable cost curve at the time (Fig. 2). If an increase in electricity consumption is greater than the existing marginal power unit can supply, another unit will participate.

The technology serving the short-term (hourly) changes in demand is usually referred as short-term marginal technology. In the CDM methodology this is referred to as "operating margin" [27]. It can vary significantly in time. For example, the marginal production unit may be totally different between day and night and between winter and summer [9]. In the Nordic countries, current marginal production is mainly coal condensing power, but it can also be supplied by other fuels such as gas, oil, peat, waste and wood, and by other technologies such as CHP [47]. Another response to a change in consumption might involve the use of

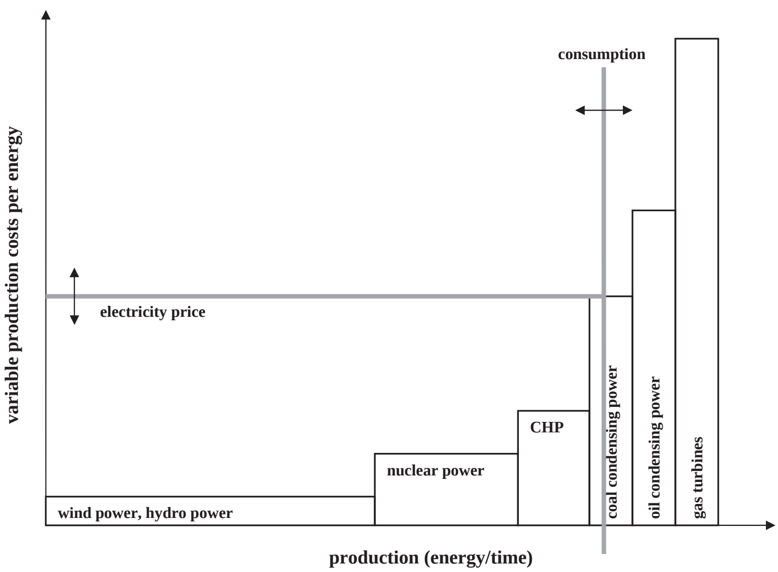

Fig. 2. An illustration of the price formation of electricity in accordance with the order of merit of the power plants that supply instant consumption, which is formed from a number of single consumption points. All of them, regardless of the type of consumption, are connected to the marginal side of production, as a decrease or increase at any consumption point has an impact on the marginal production unit. *Source*: Illustration of production structure is based on Kara et al. [47].

stored energy such as reservoir hydro power. The monetary value of stored water is determined by the forecasted water inflow, the current reservoir level, and the forecasted price of electricity [53]. If the monetary value of the water is higher than the market price of electricity, it is profitable for a hydro power producer to keep storing the water instead of selling it to the grid, and vice-versa. Reservoir hydro power helps the system to use fewer peak power plants and increases the efficiency of the system.

The short-term marginal technology may vary from technologies with nearly zero GHG emissions during operation (e.g. reservoir hydro power) to high GHG emission intensive production forms such as coal condensing power. This should be taken into account when using short-term marginal technology figures in CLCA. For example, it may be necessary to identify short-term marginal technology in order to introduce the electricity saving measurements promptly to cut peak consumption and reduce related GHG emissions efficiently. CDM methodology provides various options to determine the "operating margin" depending on the structure of the electricity generation within the grid and availability of the data [26]. The most accurate determination of "operating margin" within the CDM methodology, being "dispatch data analysis", aims to provide actual data on the short-term marginal technology.

2.3.2. Short-term feedback mechanisms

When comprehensively assessing the actual GHG impacts of changing electricity consumption, the secondary effects caused by the change need to be considered. An increase in electricity consumption may lead to a rise in the price of electricity. The size of the price increase depends mainly on the magnitude of the consumption change, the marginal production affected and potential changes in the production unit in the margin (see Fig. 2.). The price increase may generate additional impacts, such as a reduction in electricity use by some consumers, which can be seen as a negative feedback mechanism [24]. Findings by Alberini et al. [54] suggest that when electricity prices increase, households tend to substitute other inputs for energy and choose less energy-intensive appliances (or homes). On the other hand, Lijesen [55] found a low value for the real-time price elasticity between total peak demand and spot market prices, which may partly be explained by the fact that not all electricity consumers observe the spot market price.

In the short-term, an increase in electricity consumption typically results in a need to use more fuels for electricity production, which may increase fuel prices and furthermore have a reducing impact on overall electricity use. However, Mohammadi [56] found evidence of significant long-run relations only between electricity and coal prices in the U.S. between 1970 and 2007. He also concluded that there is some evidence of unidirectional short-term causality from coal and natural gas prices to electricity prices. The formation of fuel prices is a complicated issue influenced by many socio-economic factors [57]. The feedback mechanism may also be positive, and thus one cannot simply conclude that an increase in fuel consumption unambiguously increases fuel prices.

An increase in electricity consumption also leads to a rise in the absolute CO_2 emissions from electricity production especially when the marginal change is covered by the combustion of fossil fuels. The prevailing climate policy then becomes a limiting factor. For example, in the EU, electricity production is regulated under the EU ETS (EU emission trading scheme) [58]. An increase in CO_2 emissions leads to a rise in the price of emission allowances, as the amount of annual emission allowances available are defined and limited. This may mean that some other actors compensate for the CO_2 emissions resulting from a power plant and satisfy the increased electricity consumption under the EU ETS. Yet, this effect depends on the annual supply and demand of the emission allowances, as well as the mechanisms to invalidate unused emission allowances or transfer them between different years. According to Kara et al. [47], an increase in the emission allowance price also has an incremental influence on the electricity price due to the rise in the production costs of marginal electricity.

It seems obvious that prevailing market conditions and socio-economic issues related to electricity consumption influence electricity production. Eventually, a change in electricity consumption may generate a long chain of positive and negative feedback mechanisms. This makes it difficult to analyze and quantify such impacts. Furthermore, such impacts may be far-reaching, not only in space, but also in time. Thus, a long-term perspective is also required.

2.3.3. Long-term marginal technology

In addition to changes in the current electricity production mix, increased electricity consumption is likely to attract new power plant investments due to increased electricity prices. Investment decisions are further affected by a number of factors reflecting the evolution of the market or by socio-political decisions to regulate emissions. Size and timing of the initial investment together with the subsequent annual cash flows mainly determine the financial performance of a power investment [59]. Changes in electricity consumption can also affect the decisions to retire old power plants from the system. Furthermore, these decisions depend on many other factors, like anticipated fuel prices and other variable costs, as well as investment costs. The simplification of the main interactions of GHG emission impacts from changes in grid electricity consumption is illustrated in Fig. 3.

If 'new consumption' is adequately anticipated before it occurs, there is no unambiguous reason to assign short-term marginal production to this particular consumption. Such a case may occur for example, when 'a new industrial base-load consumption' comes online and a base-load nuclear power plant has been built specifically to anticipate this new consumption. Likewise, an expectation of more air-conditioning in countries with a hot climate is likely to induce investments in peak-load power plants, which will be used during the hours when air-conditioning is needed most. Thus, the expected shape of the consumption profile has implications for the investments required. Adding a constant block of consumption in a traditional electricity system would result in an increase in base-load, intermediate, and peak-load production in the short-term. Yet, in a system where a smart grid has been implemented and consumption is quite flexible, 'the new consumption' could be met with base-load power.

As regards electricity consumption from the grid, the CDM methodology provides two options [26]. First, it advises to calculate the combined margin emission factor of the applicable electricity system by using the procedures in the latest approved version of the "Tool to calculate the emission factor for an electricity system" [27]. This includes the calculation of the weighted average of "operational margin" and "build margin", referring to the group of prospective power plants whose construction and future operation would be affected by the proposed CDM projects [27]. Secondly, default values of 400 and 1300 g CO_2/kWh are provided and can be used under certain strict conditions [26].

Lund et al. [9] showed that marginal change in capacity will have to operate as an integrated part of the total energy system, and therefore, it does not necessarily represent the marginal change in electricity supply, which is likely to involve a mixture of different production technologies. By using detailed ESA (energy system analysis), they assessed that yearly average marginal technologies correspond to a wide range of GHG emission intensity, from 83.3 to 712 g CO_2-eq./kWh, under a business-as-usual 2030 projection of the Danish energy system, depending on the marginal changes in production capacities.

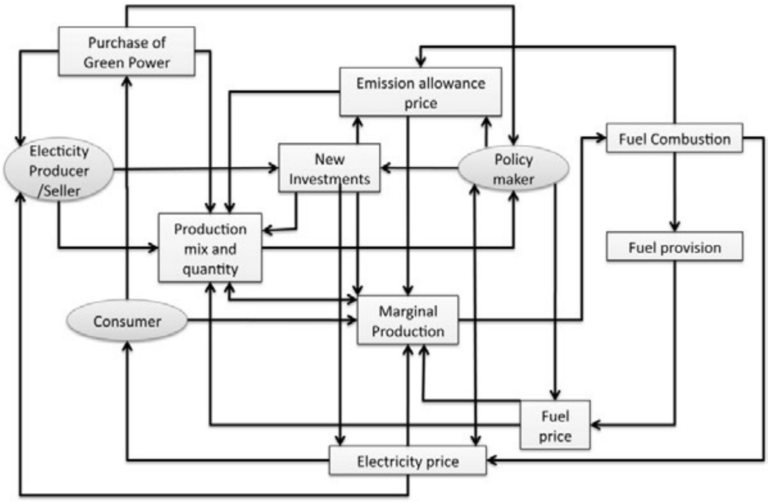

Fig. 3. An illustration of central actors, main factors, and the associated interactions of GHG emission impacts from changes in grid electricity consumption.

Sköldberg and Unger [60] analyzed the energy system and climate effects of adding or reducing 5 TWh of electricity on annual electricity demand in Sweden under various market conditions between 2009 and 2037 using the MARKAL-NORDIC energy system model. According to their results, the impact on new investments generally includes not just a single generation technology but rather a mix of several technologies, and the majority of the effects takes place outside Sweden. They found that the average CO_2 emissions of the change were approximately 700 g CO_2/kWh in several of the scenarios but only 160 g CO_2/kWh if the price of CO_2 was set relatively high (45 EUR/t).

Kiviluoma and Meibom [61] ran a power generation expansion model in order to assess the effect of different flexibility measures on wind power integration costs. In their analysis the cost of wind power was set to result in rather high levels of wind power penetration by 2035. While the time series and existing power plants were from the case of Finland, the results were affected more by the general assumptions about future costs to build and operate different power plants. The annual average CO_2 emissions for the power production varied between 7 and 140 g CO_2/kWh_e in the model runs. They also investigated the change in CO_2 emissions caused by an increase in consumption. They compared a scenario with and without plug-in electric vehicles. The 'new electricity consumption' actually reduced the total GHG emissions from electricity production. This was due to the increased flexibility of the power system; a larger fraction of the power production covered by base-load or variable power plants like nuclear and wind power was enabled in the system. In the scenarios where no new nuclear power was built, the total GHG emissions fell on the average by 13 g CO_2/kWh_e with the introduction of the plug-in electric vehicles. If this emission reduction is allocated only to the 'new consumption', as might be the case when carrying out CLCA, the decrease is as large as 330 g CO_2/kWh_e. The corresponding figures for the scenarios where nuclear power is added were 1.6 and 41 g CO_2/kWh_e, respectively.

The decisions to curb GHG emissions and increase the share of renewable energy sources are essential in the development of future GHG emissions. If major GHG emission reductions are endorsed and enforced, the electricity sector is likely to bear the greatest share of the burden (e.g. Ekholm et al. [7]). For example in the EU, there are several policy measures affecting the GHG emissions of electricity production directly or indirectly. Such measures include the binding emission reduction directives [58,62], renewable energy directive [63], and targets for energy efficiency improvements [64]. Also, the consumers may purchase 'green electricity', aiming to boost the use of renewable energy sources in many EU countries. However, the impact of purchasing 'green electricity' on new installations of renewable energy generation capacity can be rather limited in the short-term [48], especially if public policy is strong and feed-in tariffs for renewable energy are widely used [65]. Prevailing and anticipated policy measures significantly affect both the market conditions and the possibilities of consumers to influence the market conditions. Thus, any study attempting to depict future GHG emissions should take policy into account. As long as the development of climate policy is lacking, the long-term marginal technology is also subject to major uncertainties.

3. Conclusions and recommendations

GHG emissions from the production of grid electricity consumed by a certain process are typically assessed in LCA by using statistical average national figures for electricity production mix. However, there are a number of situations where the selection of this particular method is not appropriate. The recent development in LCA has led to the separation of ALCA and CLCA, which have significantly different perspectives and thus also data requirements. Both ALCA and CLCA can be applied to assess GHG emissions from electricity consumption, but only CLCA is appropriate for determining the GHG impacts of a change in consumption. The selection of the approach depends on the goal and scope of the study. The key issues to be considered in an assessment of GHG emissions from electricity consumption are summarized in Table 1.

GHG emissions of a specific power plant depend significantly on the technology and primary energy form used. Furthermore, the system boundaries set for determining individual parameters, consideration of various GHG emission components and choices for other methodological issues, such as allocation, are crucial. Fuel upstream, capital goods, and associated GHG emissions may involve significant uncertainties, and their consideration

Table 1
Key factors and issues when assessing GHG emissions of electricity consumption with attributional (ALCA) and consequential (CLCA) method.

	Attributional LCA (ALCA)	Consequential LCA (CLCA)
Research questions	– How things are (history, current, future perspective)? – Do not reflect change	– What if (history, current, future perspective)? – Reflects change
Short-term technology	– Appropriate average production mix – Spatial dimensions: e.g. power plant, electricity seller, country, market area (including exports and imports) – Temporal dimensions: e.g. instant, seasonal, annual, perennial	– Appropriate marginal production mix – Spatial dimensions: market area with transmission limitations – Temporal dimensions: e.g. instant, seasonal, annual, perennial
Feedback mechanisms	– Not considered	– Market effects (e.g. change in electricity prices and production costs)
Long-term technology	– Estimated future average production mix – The expected development of energy prices, electricity consumption and climate policy significant drivers – Spatial and temporal dimensions as above	– Comparison of GHG emissions with and without the consumption change taking into account power generation investments – The expected development of energy prices, electricity consumption and climate policy significant drivers
Major challenges and suggestions	– Determination of an appropriate production mix and the related GHG emissions – Allocation of emissions between electricity and other products in co-production units – Allocation of losses between consumers and transactions – Harmonization of methodological issues and introduction of data management system to avoid inconsistent GHG emission accounting	– Identification of the marginal technology and related consequences and determination of GHG emissions for relevant power production and other affected activities – Consideration of large uncertainties (e.g. by scenario analysis)

undoubtedly needs to be improved. The determination of GHG emissions of different electricity production forms is the first fundamental challenge encountered in both ALCA and CLCA. Due to various possible sources of uncertainty, it is not possible to objectively determine one single GHG emission figure for any of the power production forms.

Regarding ALCA, one major specific challenge is to define the appropriate production mix of the electricity (Table 1). The key dimensions to be considered are spatial (e.g. national, regional) and temporal (perennial, annual, instant). The selection of the data set may have significant impact on the results. In addition, without a harmonized methodology and data management system, there is a noticeable risk of double-counting either the GHG emissions or the share of certain electricity production forms when considering or comparing the results of various LCA studies. For example, one LCA study may use national figures, whereas another may apply figures of larger or smaller market area. The selection seems to be arbitrary, and it is difficult to determine objectively 'the correct' market area to be considered. Similar problems may be encountered with temporal overlapping, such as between peak-load hours and annual average; and with 'green electricity' if it is not separated from 'the regular electricity' elsewhere.

We conclude that national or regional production mix figures should be adjusted by electricity imports and exports, and they should only be used for analysis concerning electricity consumption at national or regional level, respectively. For history-related ALCA of a single process, figures based on the contract between the electricity seller and the customer with real-time accounting would be the most appropriate production mix figures. A general introduction of this kind of 'contract-based' approach would eliminate the prevailing problem in selecting the market area arbitrarily. However, the use of a harmonized methodology is required in order to deal with the methodological issues encountered (e.g. allocation, system boundaries). In addition, harmonized data management system is needed in order to avoid inconsistencies in the accounting procedure and to maintain the confidentiality of the data. Both of these requirements need further research and general agreements between various stakeholders. Some suggestions on the way forward are already available (e.g. Usva et al. [66]). For future-related ALCA studies, the development of the power production system should be considered by using an appropriate scenario analysis.

Regarding CLCA, the major challenge is to identify the marginal technology, and furthermore, the consequences influenced by the change (Table 1). In its simplistic form, marginal production, affected by the marginal change in the electricity consumption, is identified. Large variations between the affected technologies may occur. We acknowledge the suggestion by Mathiensen et al. [25] of using fundamentally different kinds of affected technologies for this kind of analysis. As the instant marginal GHG emissions of electricity production do not reflect the market effects beyond the immediate change, they are not suitable for describing the related consequences. Such effects may take place in the short term (e.g. increases in electricity price) and long term (e.g. investment decisions). The anticipated development of energy prices, quantity and profile of electricity consumption as well as climate policy are probably the most important market drivers of new investments in electricity production [9].

As changes in the power system are not isolated, electricity consumption and production cannot be separated from each other [9]. When attempting to study the consequences of a decision to change electricity consumption on GHG emissions, an improved understanding of the phenomenon is certainly required. It is important to recognize that not only the electricity production system is affected, but probably many other economic activities as well. Scenarios that depict the changes in economic inputs and outputs can be constructed using economic equilibrium models (e.g. Manne et al., 1995 [67], Nordhaus 1999 [68], Nijkamp et al., 2005 [69]). Yet, due to the complexity of such models, the energy system is typically described in relatively rough terms, limiting the suitability of such models for assessing, for example, GHG emission impacts. Partial equilibrium models for energy systems (e.g. Lund et al. [9], Klaassen & Riahi 2007 [6], Ekholm et al., 2009 [7]) can provide detailed information on the development of energy production to supply external energy demand. By using such models simultaneously, it is possible to create far-flung scenarios to gauge the development of GHG impacts of the economies and various actions. Yet, scenarios always involve a certain degree of uncertainty. Consequently, we suggest that an appropriate number of scenarios are carried out for CLCA in order to provide adequate perspectives on the evolution of the economies, electricity consumption and production as well as GHG emissions under various relevant market conditions.

When it is not possible to carry out a macro-level analysis on the development of future GHG emissions to support LCA, the GHG emissions of various processes or products that consume or conserve electricity need to be assessed individually. Due to the major uncertainties involved, we suggest that a single fixed value for GHG emissions of electricity consumption or conservation should not be used. However, a fixed value may be required in certain cases, such as for determining certified emission reductions of CDM projects related to electricity production or conservation. This can be appreciated but it should be noted that from a scientific viewpoint the use of a fixed value may be highly incorrect. Thus in general, the influence of uncertainties on the overall GHG balance of the concept studied should be analyzed by using an appropriate range of uncertainty. The appropriate range is likely to be lower for ALCA since average values can be used compared to CLCA. Yet, the appropriateness of the range depends on the scope and goal of the study and needs to be carefully considered. If the precautionary principle were to be followed, more conservative rather than optimistic estimates should be used.

Allocation of impacts for various economic activities is always subject to equity issues [23]. CLCA allocates GHG impacts to the decisions considered to cause the impacts. Yet, it is not necessarily fair to separate existing and new electricity consumption when considering the GHG impacts of various decisions. The GHG emissions of new consumption are directly influenced by the existing consumption and vary accordingly. From this point of view, it may be more reasonable to consider that no individual grid electricity consumption can cover the emissions of a particular production. Instead, all consumption should have the same emission intensity based on the average, reflecting the viewpoint of ALCA. On the other hand, a consumer who purchases 'green electricity' should be able to account for the GHG emissions associated with the 'green eletricity' instead of the average emissions, regardless of the actual consequences. Various viewpoints on the equity issues make it impossible to define the most appropriate method over the other ones. After all, selection of the method depends on the goal and scope of the study. This should also be taken into account in the method harmonization processes.

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